



## The influence of applied tensile stress on power loss in Co-rich amorphous Co-Fe-Si-B ribbons with induced magnetic anisotropy

Nielsen, H; Nielsen, K; Nielsen, Otto V

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## CONCLUSION

Whereas it is common practice to set off-diagonal terms in the permeability tensor to zero, experimental data and analysis have been presented that justify this assumption. Moreover, important information on the transverse characteristics of the three most common permanent magnets will help to improve field computation. The values of  $\mu'_t$  for Alnico 5 and 5-7 are particularly high compared to  $\mu'_p$ , as was the case for recoil permeability, and this would tend to enhance transverse flux in a magnet that directly experiences armature reaction in an electrical machine. If an exact model of a permanent magnet is required, then the rotation of  $M_0$  is found using (15) or (20).

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# The Influence of Applied Tensile Stress on Power Loss in Co-Rich Amorphous Co-Fe-Si-B Ribbons with Induced Magnetic Anisotropy

H. J. V. NIELSEN, K. GYNTER NIELSEN, AND O. V. NIELSEN

**Abstract**—The influence on power loss  $P_T$  of applied tensile stress  $\sigma$  in amorphous  $(\text{Co}_{0.89}\text{Fe}_{0.11})_{72}\text{Mo}_3\text{Si}_{15}\text{B}_{10}$  ( $\lambda_s > 0$ ) and  $\text{Co}_{73}\text{Mo}_2\text{Si}_{15}\text{B}_{10}$  ( $\lambda_s < 0$ ) ribbons with different induced magnetic anisotropy  $K_u$  is reported. The losses are measured under sinusoidal flux conditions at  $f = 50$  Hz,  $J_{\max} = 0.57$  T and at  $f = 400$  Hz,  $J_{\max} = 0.10$  T. Measurements are carried out on samples in a stress-relieved state and with magnetic anisotropies induced by stress or field annealing. At  $f = 50$  Hz, a minimum in  $P_T$  versus  $\sigma$  is observed. The  $\sigma$ -value ( $\sigma_{\min}$ ) corresponding to the minimum  $P_T$  increases with increasing  $|K_u|$ . At  $f = 400$  Hz, a minimum in  $P_T$  versus  $\sigma$  is observed in the samples with induced magnetic anisotropy, whereas  $\sigma_{\min} = 0$  in the stress-relieved samples. However, no correlation between  $\sigma_{\min}$  and  $K_u$  is possible from the present data.

## INTRODUCTION

IT HAS BEEN suggested that the ac core losses of amorphous alloys could be lowered by introducing more domain walls (e.g., Shilling [1]). For crystalline Fe-Ni-Mo alloys, a minimum in eddy current losses was observed when the crys-

talline and field-induced anisotropy constants were of equal magnitude (Pfeifer [2]). It was concluded that the reason for this decrease in losses was an increase in the number of domain walls in the materials. Similarly, O'Handley and Narasimhan [3] reported lower losses for a ring-laminated core of amorphous  $\text{Fe}_{40}\text{Ni}_{40}\text{B}_{20}$  alloy annealed in crossed fields (i.e., circumferential and perpendicular to the plane defined by the core) compared to cores annealed in a circumferential field only. Efforts in this direction has been reported also by Fujimori *et al.* [4], who increased the number of domain walls and decreased losses in amorphous Co-rich Fe-Co-Si-B straight ribbons by annealing in a field inclined at an angle to the ribbon axis (oblique field annealing). Annealing in a rotating magnetic field has been reported by several authors to improve initial ac permeability (and probably ac losses) in Co-rich amorphous alloys (Kohmoto *et al.* [5], Makino *et al.* [6], and Sakakima *et al.* [7]). In a recent paper [8], it was suggested to introduce two uniaxial anisotropies in the materials because the magnetic anisotropies induced by field and stress annealing of amorphous ribbons have a different origin. Field annealing of amorphous ribbons induces an easy axis in the direction of the applied magnetic field. In Co-rich amorphous ribbons, the sign of the uniaxial anisotropy induced by stress annealing depends on the sign of the magnetoelastic coupling constant  $\lambda_s$  and on the annealing temperature  $T_{\text{ann}}$  [9]. By proper adjustment of the stress annealing conditions, it is possible to make the ribbon axis an easy or a hard direction irrespective of the sign of  $\lambda_s$ .

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H. J. V. Nielsen is with Central Telecommunications Services, Posts and Telegraphs of Denmark.

K. G. Nielsen is with the Institute for Telecommunications, Building 343, The Technical University of Denmark, DK-2800 Lyngby, Denmark.

O. V. Nielsen is with the Department of Electrophysics, Building 322, The Technical University of Denmark, DK-2800 Lyngby, Denmark.

TABLE I  
THE SAMPLES AND THEIR ANNEALING TREATMENT

alloy	sp.	w mm	<t> μm	t <sub>ann</sub> h	ΔT/Δt K/min.	T <sub>ann</sub> °C	σ <sub>ann</sub> MPa	H <sub>ann</sub> kA/m	σ <sub>50Hz</sub> min MPa	σ <sub>400Hz</sub> min MPa	σ <sub>u</sub> MPa	remarks
(Co <sub>0.89</sub> Fe <sub>0.11</sub> ) <sub>72</sub> Mo <sub>3</sub> Si <sub>15</sub> B <sub>10</sub>	A	0.42	16	1		320	500		120		-85	stress-anneal
	B	0.50	16	1		320			20	0	0	stress-relief
	C	0.45	16	1		320	150		60	25	-21	stress-anneal
	D	0.80	17		-1.6	320		440		20	-9.1	field-cool. H <sub>⊥</sub>
Co <sub>73</sub> Mo <sub>2</sub> Si <sub>15</sub> B <sub>10</sub>	E	0.48	18	1		250	630			18	-14	stress-anneal
	F	0.68	21		-1.6	320		2		5	-18	field-cool. H <sub>  </sub>
	G	0.67	21	2		325				0	0	stress-relief

We report in this paper measurements of power loss on straight ribbon samples of (Co<sub>0.89</sub>Fe<sub>0.11</sub>)<sub>72</sub>Mo<sub>3</sub>Si<sub>15</sub>B<sub>10</sub> ( $\lambda_s > 0$ ) and Co<sub>73</sub>Mo<sub>2</sub>Si<sub>15</sub>B<sub>10</sub> ( $\lambda_s < 0$ ) metallic glasses with uniaxial magnetic anisotropies induced by field or stress annealing in such a way that the application of a tensile stress to a given sample sets up a uniaxial anisotropy of opposite sign to the one induced by the annealing treatment. Application of a tensile stress in the ribbon axis direction makes the ribbon axis an easy direction of magnetization ( $K_\sigma < 0$ ) for  $\lambda_s > 0$  and a hard direction of magnetization ( $K_\sigma > 0$ ) for  $\lambda_s < 0$ .

In "wide" ( $w = 13$  mm), unpolished, stress-relieved ( $\frac{1}{2}$  h at 325°C in vacuum) Fe<sub>40</sub>Ni<sub>40</sub>P<sub>14</sub>B<sub>6</sub> amorphous ribbons, the application of moderate tensile stresses ( $\sim 25$  MPa) results in a decrease in loss per cycle at  $J_{\max} = 0.75$  T at low frequencies ( $f \leq 50$  Hz) while the loss per cycle at  $f = 55$  Hz is relatively insensitive to applied stresses up to  $\sim 25$  MPa (Overshott and Blundell [10]). On the other hand, it is reported that in "narrow" ( $w \sim 2$  mm), annealed ribbons of the same amorphous alloy, a reduction of power loss of 45 percent is achieved at  $f = 55$  Hz,  $J_{\max} = 0.75$  T for an applied stress of  $\sim 20$  MPa (Blundell *et al.* [11]). This reduction in losses by the application of a tensile stress is to a large extent ascribed to an improvement of the static hysteresis losses. It seems that the "narrow" and "wide" ribbons respond somewhat differently to the applied stress.

#### EXPERIMENTAL

Amorphous ribbons (as indicated by X-ray diffraction tests) of nominal compositions (Co<sub>0.89</sub>Fe<sub>0.11</sub>)<sub>72</sub>Mo<sub>3</sub>Si<sub>15</sub>B<sub>10</sub> and Co<sub>73</sub>Mo<sub>2</sub>Si<sub>15</sub>B<sub>10</sub> were prepared by a single-roller quenching technique as described in [12].

Details of the annealing treatments of the samples used in this study are given in Table I. All annealings were done in an argon atmosphere. The field and stress was applied during the entire heat treatment. In the field annealings, the samples were quickly (i.e., within 5–10 min) heated to  $T_{\text{ann}}$  and then cooled to  $\sim 100^\circ\text{C}$  with the rate  $\Delta T/\Delta t$ . In the table,  $H_\perp$  and  $H_\parallel$  refer to fields applied perpendicular (in the ribbon plane) and parallel to the ribbon axis, respectively.

The magnitude of the induced anisotropy, described by an anisotropy constant  $K_u$ , may be determined from the static magnetization curve (ribbon axis polarization  $J$  versus applied

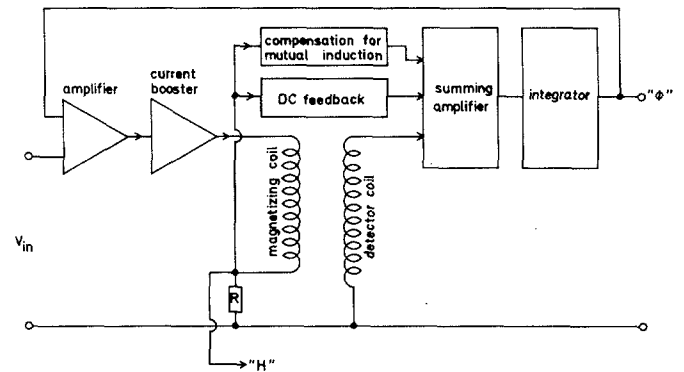


Fig. 1. Schematic diagram of the sinusoidal flux magnetizing coil system.

field  $H$ ):

$$K_u = \int_0^{J_s} H dJ$$

where  $J_s$  is the saturation polarization. In our experiments, we determined  $K_u$  from the applied stress dependence of the magnetization curve, as previously described [9]. This type of measurements makes possible determinations of negative  $K_u$  values when  $\lambda_s < 0$ . In order to facilitate comparisons between stresses applied during the power loss measurements and induced  $K_u$  values, we calculate from  $K_u$  an *equivalent* induced internal stress  $\sigma_u$  (given in Table I) by  $\sigma_u = -(2/3) K_u/\lambda_s$ . We emphasize that  $\sigma_u$  is a pure phenomenological quantity, without indicating the physical origin of  $K_u$ .

For the power loss measurements, samples of approximately 500-mm length are magnetized in a solenoid of length 150 mm and diameter 20 mm with  $\sim 350$  turns. The electromotive force (EMF) induced in a pickup coil of length 75 mm with  $\sim 9000$  turns is integrated, and the magnetic polarization  $J$  versus applied field  $H$  displayed on an oscilloscope. The power loss  $P_T$  is determined from the area of the  $J(H)$  loop under sinusoidal flux conditions. The flux in the sample is controlled by a feedback system shown in Fig. 1. The detector coil voltage is integrated to give a voltage proportional to the magnetic flux  $\Phi$ . This voltage is compared to the control voltage  $V_{\text{in}}$ , and the difference is amplified and used to determine the magnetizing current via a current booster. To assure

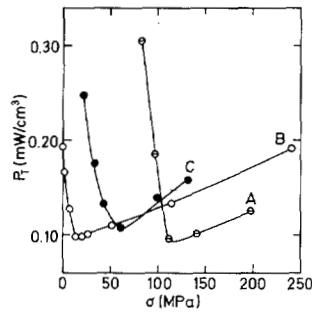


Fig. 2. Power loss  $P_T$  ( $\text{mW}/\text{cm}^3$ ) versus applied tensile stress  $\sigma$  (MPa) at  $f = 50$  Hz,  $J_{\max} = 0.57$  T for  $(\text{Co}_{0.89}\text{Fe}_{0.11})_{72}\text{Mo}_3\text{Si}_{15}\text{B}_{10}$  amorphous ribbons with various induced magnetic anisotropies: A ( $\circ$ ):  $\sigma_u = -85$  MPa, B ( $\circ$ ):  $\sigma_u = 0$  MPa, C ( $\bullet$ ):  $\sigma_u = -21$  MPa (see also Table I).

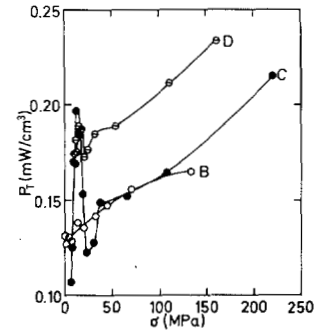


Fig. 3. Power loss  $P_T$  ( $\text{mW}/\text{cm}^3$ ) versus applied tensile stress  $\sigma$  (MPa) at  $f = 400$  Hz,  $J_{\max} = 0.10$  T for  $(\text{Co}_{0.89}\text{Fe}_{0.11})_{72}\text{Mo}_3\text{Si}_{15}\text{B}_{10}$  amorphous ribbons with various induced magnetic anisotropies: B ( $\circ$ ):  $\sigma_u = 0$  MPa, C ( $\bullet$ ):  $\sigma_u = -21$  MPa, D ( $\circ$ ):  $\sigma_u = -9.1$  MPa (see also Table I).

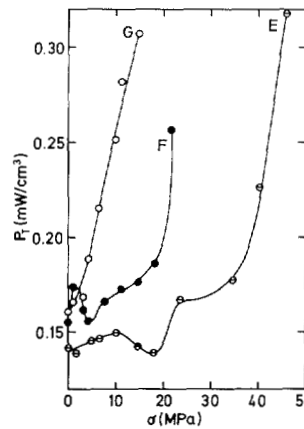


Fig. 4. Power loss  $P_T$  ( $\text{mW}/\text{cm}^3$ ) versus applied tensile stress  $\sigma$  (MPa) at  $f = 400$  Hz,  $J_{\max} = 0.10$  T for  $\text{Co}_{73}\text{Mo}_2\text{Si}_{15}\text{B}_{10}$  amorphous ribbons with various induced magnetic anisotropies: E ( $\circ$ ):  $\sigma_u = -14$  MPa, F ( $\bullet$ ):  $\sigma_u = -18$  MPa, G ( $\circ$ ):  $\sigma_u = 0$  MPa (see also Table I).

TABLE II  
SOME PHYSICAL PROPERTIES OF THE ALLOYS

alloy	$T_C$ $^{\circ}\text{C}$	$T_X$ $^{\circ}\text{C}$	$d$ $\text{kg}/\text{m}^3$	$J_s$ T	$\lambda_s$	$E$ MPa	$\rho$ $\mu\Omega/\text{m}$
$(\text{Co}_{0.89}\text{Fe}_{0.11})_{72}\text{Mo}_3\text{Si}_{15}\text{B}_{10}$	308	525	8390	0.75	$3.1 \cdot 10^{-6}$	$0.15 \cdot 10^6$	1.37
$\text{Co}_{73}\text{Mo}_2\text{Si}_{15}\text{B}_{10}$	293	518	8550	0.70	$-2.9 \cdot 10^{-6}$	$0.14 \cdot 10^6$	1.23

dc stability, a special dc feedback around the coils is established. Furthermore, a feedback system for compensation of the mutual induction between the coils with no sample inserted is included.

Measurements of power loss versus applied tensile stress  $\sigma$  were done at  $f = 50$  Hz,  $J_{\max} = 0.57$  T on samples A, B, C (see Table I and Fig. 2) and at  $f = 400$  Hz,  $J_{\max} = 0.10$  T on samples B, C, D, E, F, G (see Table I and Figs. 3 and 4) with applied stresses from 0–250 MPa.

The applied stress was determined from the applied load and the cross-sectional area of the sample, which in turn was determined from the weight, length, and mass density of the ribbon. The mass densities of the present alloys were calculated from values from the literature for the  $(\text{Co}, \text{Fe})_{75}\text{Si}_{15}\text{B}_{10}$  system as described previously [12].

Some relevant physical properties of these alloys are given in Table II: Curie temperature  $T_C$ , crystallization temperature  $T_X$  (heating rate  $\sim 10$  K/min), mass density  $d$ , room temperature saturation polarization  $J_s$ , magnetostriction constant  $\lambda_s$ , and Young's modulus  $E$  (all from [8]) and room temperature electrical resistivity  $\rho$  [12].

#### RESULTS AND DISCUSSION

As seen in Fig. 2, our "narrow" ( $0.4 \leq w \leq 0.8$  mm) ribbons show an initial decrease in power loss with applied stress at  $f = 50$  Hz,  $J_{\max} = 0.57$  T, as also observed by Blundell *et al.* [11]. For our alloys, the losses show a minimum and start to increase with increasing tensile stress. As seen from Fig. 2 and Table I, the stress  $\sigma_{\min}$  corresponding to the minimum in  $P_T$  increases with increasing induced anisotropy  $K_u$  (i.e., de-

creasing  $\sigma_u$ ), but these data do not allow further correlation of  $\sigma_{\min}$  to  $\sigma_u$ .

It could be mentioned that the  $P_T$  versus  $\sigma$  curve for sample *B* in the as-quenched state was nearly identical to the one shown in Fig. 2 for a stress-relieved condition; i.e., no large effect of stress relief on losses is observed for these alloys in contrast to the Fe-B and Fe-Ni-P-B alloys reported by Blundell *et al.* [11]. This may be due to the small value of the magnetoelastic coupling constant of our alloys compared to the Fe- or Fe-Ni-based alloys.

It should be emphasized that the zero field annealings, i.e., the stress relief and stress annealings, are all conducted at a temperature above the Curie temperature (see Tables I and II) so that any deterioration of low-field magnetic properties due to domain wall stabilization may be excluded (see, e.g., Fujimori *et al.* [13]).

Figs. 3 and 4 show the power loss versus applied tensile stress at  $f = 400$  Hz,  $J_{\max} = 0.10$  T for  $(\text{Co}_{0.89}\text{Fe}_{0.11})_{72}\text{Mo}_3\text{Si}_{15}\text{B}_{10}$  and  $\text{Co}_{73}\text{Mo}_2\text{Si}_{15}\text{B}_{10}$  amorphous alloys with anisotropies built in by appropriate field and stress annealings as described in the Introduction (samples *C, D, E, F* in Table I). For comparison, data for the two alloys in a stress-relieved state are included (samples *B, G* in Table I). A maximum followed by a minimum in the  $P_T$  versus  $\sigma$  curves is observed for the samples with preinduced anisotropies, whereas these extrema are absent in the stress-relieved-only samples.

### CONCLUSION

The initial reduction in  $P_T$  versus  $\sigma$  at 50 Hz (Fig. 2) is thought to be due to an improvement in the static hysteresis losses [11].

The origin of the minimum in  $P_T$  versus  $\sigma$  at 400 Hz (Figs. 3 and 4) is thought to be a more or less complete cancellation of the lowest order terms in the expressions for the free energies of the two uniaxial anisotropies, leaving only higher order terms in the expression for the total free energy [8]. The complicated course of the curves in Figs. 3 and 4 suggests that the cancellation is not at all complete for these samples, and one might suspect that an ideal situation and thus a correlation between the preinduced and tension-induced anisotropies is very difficult to obtain.

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